PERIÓDICO TCHÊ QUÍMICA
ARTIGO ORIGINAL

PROBLEMA NÃO ESTACIONÁRIO DO PLANO DE DIFRAÇÃO DE ONDA DE PRESSÃO OBLÍQUA EM CONCHA FINA NA FORMA DE CILINDRO PARABÓLICO

NON-STATIONARY PROBLEM OF THE PLANE OBLIQUE PRESSURE WAVE DIFFRACTION ON THIN SHELL IN THE SHAPE OF PARABOLIC CYLINDER

НЕСТАЦИОНАРНАЯ ЗАДАЧА ДИФРАКЦИИ ПЛОСКОЙ КОСОЙ ВОЛНЫ ДАВЛЕНИЯ НА ТОНКОЙ ОБОЛОЧКЕ В ФОРМЕ ПАРАБОЛИЧЕСКОГО ЦИЛИНДРА

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RESUMO

Um problema de plano não estacionário da dinâmica do invólucro elástico fino na forma de cilindro parabólico imerso no fluido sob o impacto da onda de pressão oblíqua plana é considerado. Para resolver este problema, é construído um sistema de equações na formulação relacionada. Com isto, os problemas de hidroelasticidade são reduzidos às equações da dinâmica da casca, o efeito de amortecimento do fluido é levado em conta pela introdução de um operador tipo convolução integral no domínio do tempo que na primeira aproximação permite contabilizar a porosidade capilar do material da casca. O núcleo do operador é uma função de transição de superfície do problema auxiliar da difração da onda de pressão acústica do plano em uma superfície convexa. O problema é resolvido aproximadamente com base na hipótese da camada fina. As equações integral e diferencial do movimento da casca são resolvidas numericamente com base na discretização de diferenças dos operadores diferenciais e na representação do operador integral pela soma usando a regra do trapézio.

Palavras-chave: *onda de pressão plana não estacionária, cascas finas, teoria de primeira ordem, funções de superfície transitória, contabilidade de material capilar poroso.*

ABSTRACT

A non-stationary plane problem of the dynamics of thin elastic shell in the form of parabolic cylinder immersed in the fluid under the impact of the plane oblique pressure wave is considered. To solve this problem, a system of equations in the related formulation is constructed. Herewith, the hydroelasticity problems are reduced to the equations of the shell dynamics, the damping effect of fluid is taken into account by introducing an integral convolution type operator in the time domain which in the first approximation allows for accounting the capillary porosity of the shell material. The operator core is a surface transition function of the auxiliary problem of the plane acoustic pressure wave diffraction on a convex surface. The problem is solved approximately based on the thin layer hypothesis. The integral and differential equations of shell motion are solved numerically based on the difference discretization of differential operators and the representation of the integral operator by sum using the trapezium rule.

Keywords: *plane non-stationary pressure wave, thin shells, first-order theory, transient surface functions, accounting of capillary-porous material.*

ABSTRACT

Рассматривается плоская нестационарная задача динамики тонкой упругой оболочки в виде параболического цилиндра, погруженной в жидкость, под действием плоской косой волны давления. Для решения поставленной задачи строится система уравнений в связанной постановке. При этом задачи гидроупругости приводится к уравнениям динамики оболочки, демпфирующее влияние жидкости учитывается введением интегрального оператора типа свертки во временной области, что в первом

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приближении дает учет капиллярно-пористости материала оболочки. Ядро оператора является поверхностной переходной функцией вспомогательной задачи дифракции плоских акустических волн давления на выпуклой поверхности. Задача решается приближенно на основе гипотезы тонкого слоя. Интегро-дифференциальные уравнения движения оболочки решаются численно на основе разностной дискретизации дифференциальных операторов и представления интегрального оператора суммой с использованием правила трапеций.

Keywords: *плоская нестационарная волна давления, тонкие оболочки, теория первого порядка, функции переходные поверхностные, учет капиллярно-пористый материал.*

1. INTRODUCTION

The diffraction of weak shock waves in fluid based on the approximate models is studied. The solution of the problem is based on the apparatus of transition functions, which are the fundamental solutions of the non-stationary initial boundary value problem of the acoustic medium diffraction on a smooth convex surface.

The problems of the acoustic waves diffraction on the second-order canonical surface and based on the thin-layer hypothesis are studied. The fundamental solutions at the zero viscous damping coefficients are built.

The integral and differential equations of the elastic shells motion that are susceptible to shear under the action of weak shock waves of various shapes in the acoustic medium are obtained based on the constructed transition functions. The interaction with the surrounding continuous medium is modeled by the integral terms of the equations.

For the numerical solution of the integral and differential equations of the shell motion, the difference schemes are constructed, and their convergence is investigated. The difference schemes built on different templates are compared based on the model problem of the plane acoustic wave diffraction on the parabolic cylinder, and the use of five-point difference scheme by the spatial variable with the three-point scheme by the time variable is proposed. This type of problem was considered earlier (Formalev *et al.,* 2015, 2016a, 2016c, 2016b, 2017a, 2017b, 2018b, 2018c; Kolesnik *et al.,* 2015; Formalev and Kolesnik, 2016, 2017, 2018; Okonechnikov *et al.,* 2016; Prokofiev *et al.,* 2016; Babaytsev *et al.,* 2017; Gidaspov and Severina, 2017; Lurie *et al.,* 2017; Bulychev *et al.,* 2018a, 2018b, 2018c; Kuznetsova *et al.,* 2018).

The paper deals with the problem of diffraction of non- stationary plain oblique pressure wave on a thin elastic shell in the shape of a parabolic cylinder placed in the acoustic medium. To determine the hydrodynamic pressure acting on the shell, a transition function built based on the thin-layer hypothesis is used (Gorshkov *et al.,* 2003a, 2003b; Medvedsky and Rabinsky, 2007; Lark *et al.,* 2010). The integration of the shell motion equations of Timoshenko type obtained using the Maple 9.0 software is carried out by the finite difference method using Matlab 6.5.

2. METHODOLOGY

The hypotheses which allow analytically for constructing the transition function of this problem are substantiated based on the solution of the problem of the acoustic wave diffraction on a curvilinear convex obstacle.

Thin layer hypothesis, which is a generalization of the well-known hypothesis of plain reflection due to the obstacle curvature, is formulated. The approximate solutions obtained based on the thin layer hypothesis are compared, with exact solutions of model problems, and the effectiveness of the hypothesis application for determining the pressure in the acoustic wave on the surface of convex obstacle is demonstrated.

The non-stationary problem of the acoustic medium dynamics is formulated in the curvilinear orthogonal coordinate system normally associated with an obstacle – a rigid body or an elastic shell.

To determine the transition functions in the acoustic environment Laplace integral transforms with respect to time and Fourier transform over the coordinate are used.

To assess the accuracy of the applied approximate approach to the solution of problems that do not allow an exact analytical solution an explicit finite-difference scheme for integrating the dynamics equations of acoustic medium in the curvilinear coordinate system normally associated with obstacle, and the convergence of the discrete finite-difference analog to the original initial boundary value problem has been built.

3. RESULTS AND DISCUSSION:

2.1. Problem definition

The mathematical definition of the problem is as follows.

– Acoustic medium (Equations 1-2) (Medvedsky and Rabinsky, 2007);

– Elastic isotropic thin shell (Equations 3-5) (Rabinskiy, 2018).

Here φ is the velocity potential in the acoustic medium, p is the pressure in the reflected and emitted waves, $\mathbf{v}$ is the velocity vector of acoustic medium, u_i are the generalized displacements of the middle shell surface, $\mathbf{L}_{ij}$ are the known differential operators determined by the shell geometry, δ_{ij} are Kronecker symbols. Relations (5) determine by means of operators $\mathbf{N}^{(m)}(u_i)$ the boundary conditions depending on the shape of the shell and its fixation in space.

Further, the problem is solved in a dimensionless form. Herewith, all the linear dimensions are related to the focal distance a, velocity – to the sound velocity in the acoustic medium c_0, magnitudes having the pressure dimensions – to the complex $\rho_0 c_0^2$, time τ – to tc_0/a.

From the conditions of the joint movement of shell and the adjacent particles of the acoustic medium, the impermeability conditions are derived in Equation 6, where φ_* is the velocity potential of the wave falling on the shell, $\partial/\partial n$ is the derivative with respect to the outward normal to the shell, w is the shell deflection.

The pressures p_1 and p_2 in the reflected and radiated waves can be found using a transition function $G(x^i,\tau)$ constructed within the thin layer hypothesis (Equations 7-9, where an asterisk denotes a convolution operation with respect to time τ).

Herewith, the influence function $G(x^i,\tau)$ satisfies the following initial-boundary value problem (Equations 10-12, where $\delta(\tau)$ is the Dirac delta function).

2.2. Determination of hydrodynamic pressure on the shell

Let us introduce a curvilinear coordinate system (ξ^1,ξ^3) associated with curve Γ. Let the radius $\mathbf{r}_0(\xi^1)$ be the vector of curve Γ, and let $\mathbf{n}_0(\xi^1)$ be the unit normal vector to the shell surface in the shape of parabolic cylinder. Then the curvilinear coordinate system is determined in Equation 13 (the differentiation is indicated by a subscript).

The metric tensor components will be as in Equation 14, where $k = k(\xi^1)$ is the curvature of the curve Γ.

In the first approximation, we can assume that the main contribution to the hydrodynamic load is obtained from the motion of the medium along the normal to the surface (Gorshkov *et al.,* 2003a, 2003b; Medvedsky and Rabinsky, 2007; Lark *et al.,* 2010). In this case, the motion of medium along the surface Γ can be neglected. Therefore, the derivatives with respect to coordinate ξ^1 in (1.1) can be set identically equal to zero, and the Laplace operator can be calculated on the cylinder surface $\xi^3 = 0$. The latter corresponds to the Laplace operator Δ_ξ in (Equation 10). Therefore, the initial boundary value problem (Equations 10-12) will be as in Equations 15-17.

The influence transition function $G_0(\xi^1,\tau)$ on the obstacle surface Γ is found by the operational method and is as in Equations 18-19, where $F_2\left([a],[b,c],z\right)$ is the generalized hypergeometric function (Gorshkov et al., 2003a).

In this case, the expressions for pressure in the reflected and radiated waves with regard to equations 7-8 are presented as in equations 20-22.

2.3. Plane oblique pressure wave diffraction on elastic shell in the form of parabolic cylinder

The pressure behind the wavefront in the coordinate system $Ox^i\ (i = 1,2)$ is set by relation, which is shown in Equations 23-24, where constant C determines the wave front position at the initial moment of time $\tau = 0$; p_0 is the amplitude pressure (Gorshkov *et al.,* 2003a).

To determine the constant C and coordinates of the tangency point, we obtain the system of equations 25-26, where ξ_0^1 is the parameter corresponding to the tangency point A) (Gorshkov *et al.,* 2003b).

The velocity potential of incident wave $\varphi_*(x^j, \tau)$ corresponds to pressure (Equations 23, 27).

For the derivative by normal to the surface of the incident wave potential from (Equation 27), we obtain Equations 28-29.

Taking into account Equations 28-29 the pressure in the reflected wave is determined in Equation 30, where the function $G_p(\xi^1, \tau)$ means $G_p(\xi^1, 0, \tau)$ at the mean surface curvature $k(\xi^1)/2$.

Relation (30) allow approximately within the thin layer hypothesis determine the reflected pressure in the diffraction problems.

Let us consider an example of solving the problem of diffraction of plane oblique pressure wave on various obstacles. Herewith, let us suggest $\xi^1 = \xi$ everywhere.

At the initial time $\tau = 0$ the shell and medium are in the unperturbed state which corresponds to the homogeneous initial conditions (Equations 2 and 4).

Let us consider the problem of diffraction of plane step-like pressure wave on the elastic rigid stationary curvilinear obstacle. An oblique plane acoustic wave with a front that makes an angle ϑ with the axis Ox^1 at the initial time $\tau = 0$ touches at point A (Figure 1) the surface of the cylinder with a guide Γ.

The guide of thin elastic shell in the shape of a parabolic cylinder Γ is parameterized as follows.

This surface with focal distance $a > 0$ in the Cartesian rectangular coordinate system Ox^1x^2 is determined in Equation 31, where value a is selected as the linear dimension in (1.2.23): $L = a$.

The main curvature is determined by the formula (1.2.28) where the average curvature takes the form of $k(\xi)/2$ and the components of the normal vector are set by the expressions 32-33 for the case of plane problem (Formalev et al., 2018a; Rabinskiy and Tushavina, 2018, 2019; Zhavoronok, 2018).

Herewith, constant C and coordinate of tangency point is found from the system of equations 25-26 and is as in equation 34.

The resolving equations for the shell can be written in the operator form (Equations 35-36), suitable for the numerical solution of the discrete analogue of the problem ($\mathbf{L}$ is the linear operator of the problem, $\mathbf{p}$ is the vector function of the right-hand sides) (Rabinskiy, 2018; Rabinskiy and Tushavina, 2019).

In general, the construction of resolving equations 35-36 in the curvilinear coordinates associated with the surface of arbitrary shape is very difficult. At the same time, the use of computer algebra systems that support the basic operations of tensor analysis allows for automating the process of transition from the general formulation of the problem to its operator record in the particular coordinate system. In this case, the Maple 9.0 computer algebra system with Tensor extension package was used.

The results of solution are presented in Figures 2–5 for the steel thin shell in the shape of parabolic cylinder (density $\rho = 7200\,\text{кг}/\text{м}^3$, elastic modulus $E = 2 \cdot 10^6$ MPa, Poisson's ratio $\nu = 0{,}3$, shell thickness $h = 0{,}01$ m, ratio between semi-axes $b/a = 0.5$) placed in water (density $\rho_0 = 1000\,\text{кг}/\text{м}^3$, sound velocity $c_0 = 330\,\text{м}/\text{с}$, β). The pressure intensity at the front of the incident wave at the initial time $p_0 = 10^4\ \Pi\text{a}$.

Figures 2-3 show the dependences of the total pressure and deflection on the coordinate at the moments of the dimensionless time $\tau =$ 0.4, 0.6, 0.625, 1.0. The dashed line shows the same curves with regard to the damping in liquid.

4. CONCLUSIONS:

The paper based on the critical analysis of existing methods for constructing the accurate and approximate solutions for the problem of the weak shock wave diffraction in the acoustic medium on the rigid or deformable convex obstacle is justified by the use of the apparatus of transition functions.

The pressure profiles of plane waves with arbitrary orientation of the front and spherical or cylindrical waves with arbitrary source location diffracting on the parabolic cylinder are constructed.

The examples show the effectiveness of the applied method of semi-analytical calculation of pressure on the rigid obstacle.

The integral and differential equations of the elastic shells motion that are susceptible to shear under the action of weak shock waves of various shapes in the acoustic medium are obtained based on the constructed transition functions. The interaction with the surrounding continuous medium is modeled by the integral terms of the equations.

The solutions of the problems of the dynamics of non-circular cylindrical shells in the plane formulation and shells of revolution in the spatial formulation are constructed based on the developed method. Numerical examples show the effectiveness of the method when solving the problems of non-stationary interaction of shells with the surrounding continuous medium.

The pressure profiles and kinematic parameters of plane waves with arbitrary orientation of the front diffracted on the parabolic cylinder in the plane formulation of the problem are constructed.

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$$\frac{\partial^2\varphi}{\partial\tau^2}=\Delta\varphi,\ p=-\frac{\partial\varphi}{\partial\tau},\ \mathbf{v}=\operatorname{grad}\varphi \qquad \text{(Eq. 1)}$$

$$\left.\varphi\right|_{\tau=0}=\left.\dot{\varphi}\right|_{\tau=0}=0 \qquad \text{(Eq. 2)}$$

$$\frac{\partial^2 u_i}{\partial\tau^2}=\mathbf{L}_{ij}(u_j)+(p_*+p)\delta_{i3}\quad (i,j=1,2,3) \qquad \text{(Eq. 3)}$$

$$\left.u_i\right|_{\tau=0}=\left.\frac{\partial u_i}{\partial\tau}\right|_{\tau=0}=0 \qquad \text{(Eq. 4)}$$

$$\left.\mathbf{N}^{(m)}(u_i)\right|_{\xi^1=\xi^1_k}=0\qquad (k=1,2) \qquad \text{(Eq. 5)}$$

$$\frac{\partial w}{\partial\tau}=\left.\frac{\partial\varphi_*}{\partial n}\right|_{\Gamma}+\left.\frac{\partial\varphi}{\partial n}\right|_{\Gamma} \qquad \text{(Eq. 6)}$$

$$p_1(\xi^1,\tau)=\frac{\partial\varphi_*(\xi^1,0,\tau)}{\partial n}*G_p(\xi^1,\tau) \qquad \text{(Eq. 7)}$$

$$p_2(\xi^1,\tau)=\frac{\partial w}{\partial t}(\xi^1,\tau)*G_p(\xi^1,\tau) \qquad \text{(Eq. 8)}$$

$$p=p_1+p_2,\qquad G_p(\xi^1,\tau)=-\left.\frac{\partial G(x^i,\tau)}{\partial\tau}\right|_{\Gamma} \qquad \text{(Eq. 9)}$$

$$\frac{\partial^2 G}{\partial\tau^2}=c_0^2\Delta_\xi G \qquad \text{(Eq. 10)}$$

$$\left.G\right|_{\tau=0}=\left.\frac{\partial G}{\partial\tau}\right|_{\tau=0}=0 \qquad \text{(Eq. 11)}$$

$$\left.\frac{\partial G}{\partial n}\right|_{\Gamma} = \delta(\tau),\ \ G(r,\tau) = O(1)\ \text{при}\ r \to \infty \qquad \text{(Eq. 12)}$$

$$\mathbf{r}(\xi^1,\xi^1) = \mathbf{r}_0(\xi^1) - \xi^3\mathbf{n}_0(\xi^1) \qquad \text{(Eq. 13)}$$

$$g_{11} = H_1^2 = \boldsymbol{\tau}^2\left[1 + 2\xi^3 k + \left(\xi^3 k\right)^2\right],\ \ g_{12} = 0,\ \ g_{22} = H_2^2 = 1 \qquad \text{(Eq. 14)}$$

$$\frac{\partial^2 G}{\partial \tau^2} = \frac{c_0^2}{H_1}\left[\frac{\partial}{\partial \xi^1}\left(H_1\frac{\partial G}{\partial \xi^1}\right)\right]\Bigg|_{\xi^3=0} \qquad \text{(Eq. 15)}$$

$$G\big|_{\tau=0} = \left.\frac{\partial G}{\partial \tau}\right|_{\tau=0} = 0 \qquad \text{(Eq. 16)}$$

$$\left.\frac{\partial G}{\partial \xi^3}\right|_{\xi^3=0} = \delta(\tau),\ \ G(r,t) = O(1)\ \text{при}\ r \to \infty \qquad \text{(Eq. 17)}$$

$$G_0(\xi,\tau) = -H(\tau)R(z); \qquad \text{(Eq. 18)}$$

$$R(z) = -z + {}_1F_2\left(\left[-\frac{1}{2}\right],\left[\frac{1}{2},1\right],-\frac{z^2}{4}\right),\ \ z = \frac{k(\xi)\tau}{2}. \qquad \text{(Eq. 19)}$$

$$p_1(\xi^1,\tau) = -\int_0^\tau \frac{\partial \varphi_*(\xi^1,0,\tau - t)}{\partial \xi^2} G_p(\xi^1,t)dt \qquad \text{(Eq. 20)}$$

$$p_2(\xi^1,\tau) = -\int_0^\tau \frac{\partial u_1(\xi^1,\tau - t)}{\partial t} G_p(\xi^1,t)dt \qquad \text{(Eq. 21)}$$

$$G_p(\xi^1,\tau) = \frac{\partial G_0(\xi^1,\tau)}{\partial \tau} \qquad \text{(Eq. 22)}$$

$$p_*(x^i,\tau) = p_0 H\left(\tau - f(x^i,\vartheta)\right) \qquad \text{(Eq. 23)}$$

$$f(x^i,\vartheta) = x^1\cos\vartheta + x^2\sin\vartheta + C \qquad \text{(Eq. 24)}$$

$$x^1(\xi_0^1)\cos\vartheta + x^2(\xi_0^1)\sin\vartheta + C = 0 \qquad \text{(Eq. 25)}$$

$$\frac{dx^1(\xi_0^1)}{d\xi^1}\cos\vartheta + \frac{dx^2(\xi_0^1)}{d\xi^1}\sin\vartheta = 0 \qquad \text{(Eq. 26)}$$

$$\varphi_*(x^j,\tau) = -p_0\left(\tau - f(x^j,\vartheta)\right)_+ \qquad \text{(Eq. 27)}$$

$$\left.\frac{\partial \varphi_*(\xi^j,\tau)}{\partial \eta}\right|_{\eta=0} = p_0 \frac{\partial f(x^j,\vartheta)}{\partial x^k}\frac{\partial x^k}{\partial \eta} H\left(\tau - f(x^j,\vartheta)\right)\Big|_{\eta=0} = \quad \text{(Eq. 28)}$$

$$= p_0 \left(n_0^1 \cos\vartheta + n_0^2 \sin\vartheta\right) H\left(\tau - f_0(\xi^1,\vartheta)\right),$$

$$f_0(\xi^1,\vartheta) = f\left(x^i\left(\xi^j\right),\vartheta\right)\Big|_{\eta=0} \quad \text{(Eq. 29)}$$

$$p_1(\xi^1,\tau) = -p_0\left(n_0^1 \cos\vartheta + n_0^2 \sin\vartheta\right) \int_0^{\tau - f_0(\xi^1,\vartheta)} G_p(\xi^1,t)dt = \quad \text{(Eq. 30)}$$

$$= -p_0\left(n_0^1 \cos\vartheta + n_0^2 \sin\vartheta\right) G_0(\xi^1, \tau - f_0(\xi^1,\vartheta)),$$

$$\Gamma:\ x^1 = \frac{\xi^2}{2}, \quad x^2 = \xi,\ \xi \in \mathbf{R} / \quad \text{(Eq. 31)}$$

$$k(\xi) = \frac{1}{\left(1+\xi^2\right)^{3/2}} \quad \text{(Eq. 32)}$$

$$n_0^1 = \frac{1}{\sqrt{1+\xi^2}},\ n_0^2 = -\frac{\xi}{\sqrt{1+\xi^2}}. \quad \text{(Eq. 33)}$$

$$\xi_0 = -\mathrm{tg}\vartheta,\ C = \frac{1}{2}\mathrm{tg}\vartheta \sin\vartheta. \quad \text{(Eq. 34)}$$

$$\frac{\partial^2 \mathbf{u}}{\partial \tau^2} = \mathbf{L}\mathbf{u} + \mathbf{p} \quad \text{(Eq. 35)}$$

$$\mathbf{L} = \mathbf{C}\frac{d}{d\xi^2} + \mathbf{B}\frac{d}{d\xi} + \mathbf{A} \quad \text{(Eq. 36)}$$

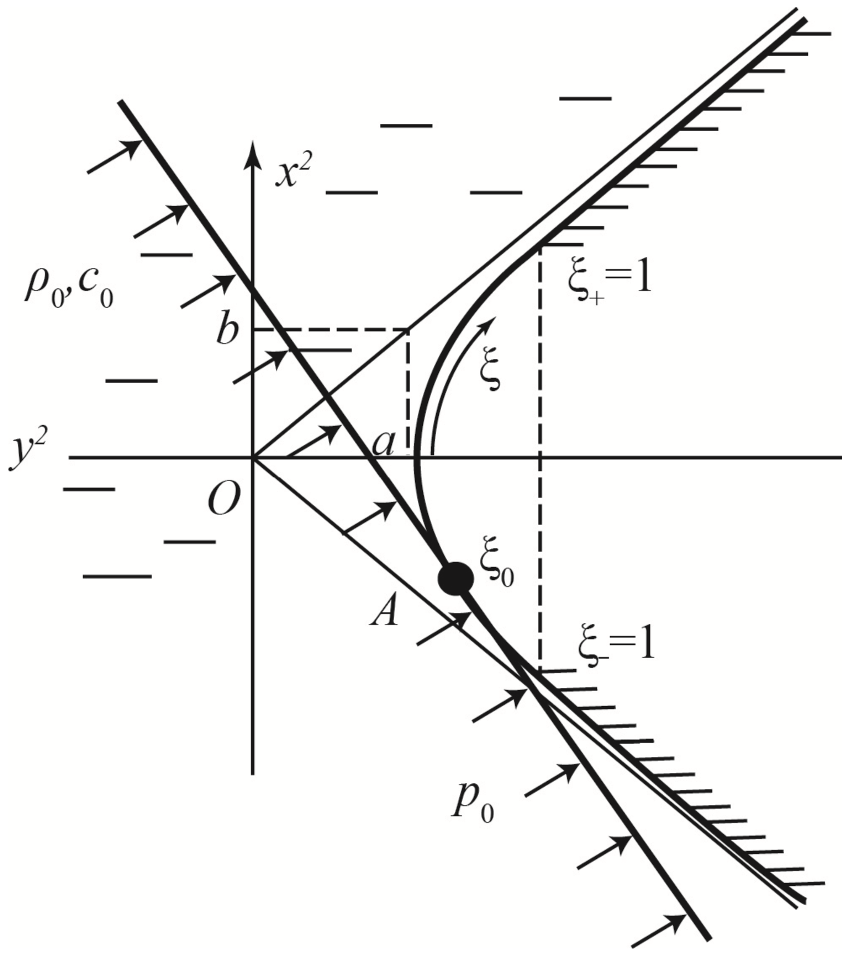

Figure 1. *The diffraction of plane step-like pressure wave on the elastic rigid stationary curvilinear obstacle*

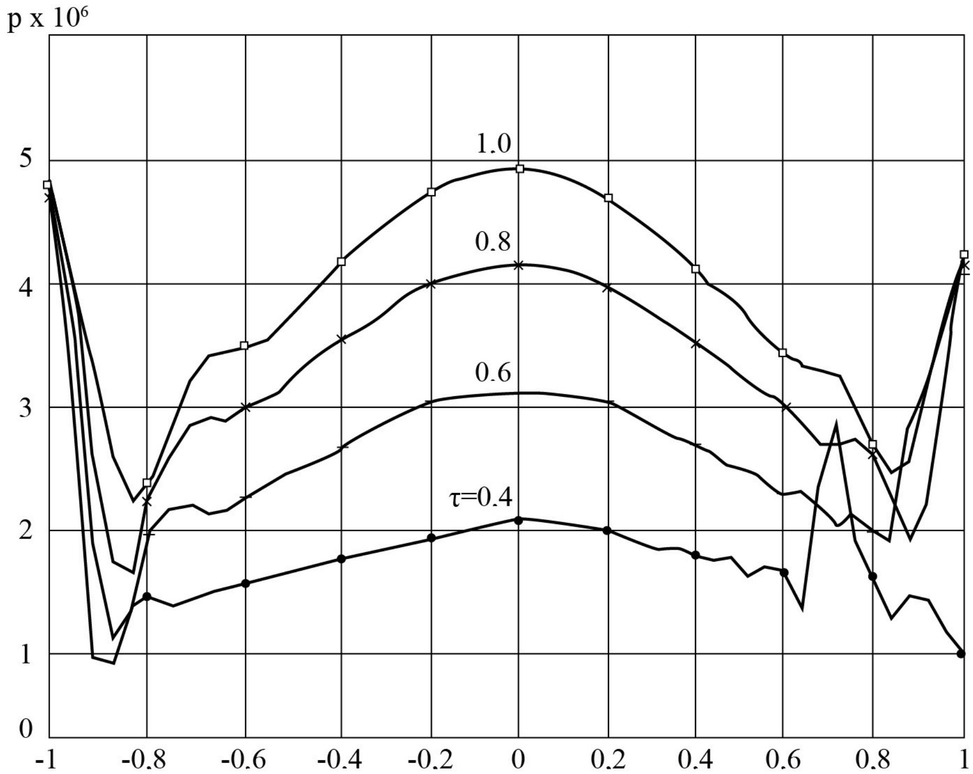

Figure 2. *Distribution of total pressure at different time intervals*

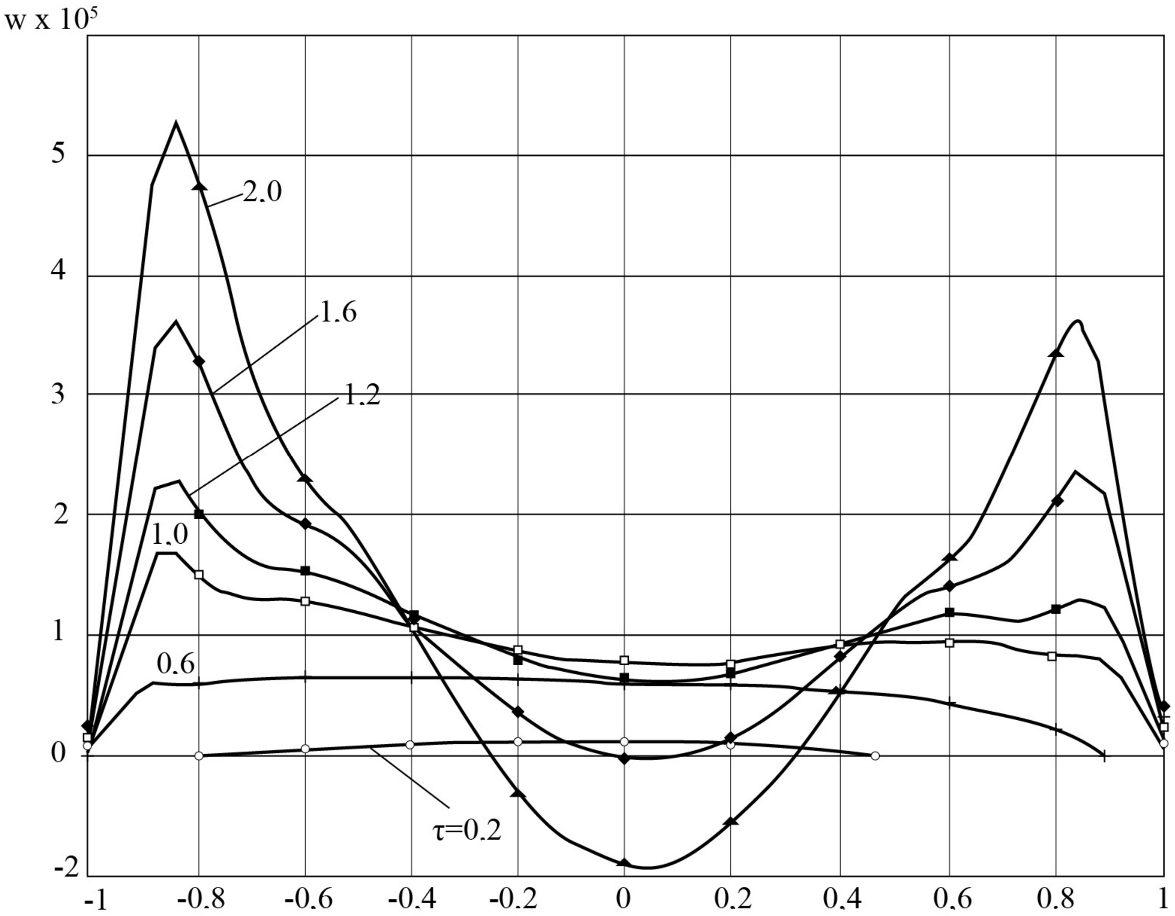

Figure 3. *Distribution of shell deflection at different time intervals*